
Modern Optical Engineering

The Design of Optical Systems

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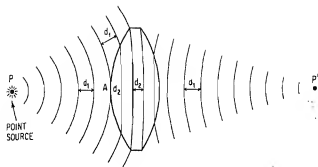


Figure 1.8 The passage of a wave front through a converging, or positive, lens element.

surface. It can be seen that the wave front has been retarded by the medium of the lens and that this retardation has been greater in the thicker central portion of the lens, causing the curvature of the wave front to be reversed. At the left of the lens the light from P was diverging, and to the right of the lens the light is now converging in the general direction of point P' . If a screen or sheet of paper were placed at P' , a concentration of light could be observed at this point. The lens is said to have formed an image of P at P' . A lens of this type is called a converging, or positive, lens.

Figure 1.8 diagrams the action of a convex lens—that is, a lens which is thicker at its center than at its edges. A convex lens with an index higher than that of the surrounding medium is a converging lens, in that it will increase the convergence (or reduce the divergence) of a wave front passing through it.

In Fig. 1.9 the action of a concave lens is sketched. In this case the lens is thicker at the edge and thus retards the wave front more at the edge than at the center and increases the divergence. After passing through the lens, the wave front appears to have originated from the neighborhood of point P' , which is the image of point P formed by the lens. In this case, however, it would be futile to place a screen at P' and expect to find a concentration of light; all that would be observed



Figure 1.9 The passage of a wave front through a diverging, or negative, lens element.

would be the general illumination produced by the light emanating from P . This type of image is called a *virtual* image to distinguish it from the type of image diagrammed in Fig. 1.8, which is called a *real* image. Thus a virtual image may be observed directly or may serve as a source to be reimaged by a subsequent lens system, but it cannot be produced on a screen.

The path of a ray of light through the lenses of Figs. 1.8 and 1.9 is the path traced by a point on the wave front. In Fig. 1.10 several ray paths have been drawn for the case of a converging lens. Note that the rays originate at point P and proceed in straight lines (since the media involved are isotropic) to the surface of the lens where they are refracted according to Snell's law (Eq. 1.3.) After refraction at the second surface the rays converge at the image P' . (In practice the rays will converge exactly at P' only if the lens surfaces are suitably chosen surfaces of rotation, usually nonspherical, whose axes are coincident and pass through P .) This would lead one to expect that the concentration of light at P' would be a perfect point. However, the wave nature of light causes it to be diffracted in passing through the limiting aperture of the lens so that the image, even for a "perfect" lens, is spread out into a small disc of light surrounded by faint rings as discussed in Chap. 6.

In Fig. 1.11 a wave front from a source so far distant that the curvature of the wave front is negligible, is shown approaching a prism, which has two flat polished faces. As it passes through each face of the prism, the light is refracted downward so that the direction of propagation is deviated. The angle of deviation of the prism is the angle between the incident ray and the emergent ray. Note that the wave front remains plane as it passes through the prism.

If the radiation incident on the prism consisted of more than one wavelength, the shorter-wavelength radiation would be slowed down

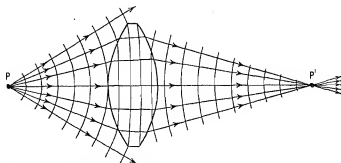


Figure 1.10 Showing the relationship between light rays and the wave front in passing through a positive lens element.

FOURTH EDITION

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INTRODUCTION TO PHYSICS FOR SCIENTISTS AND ENGINEERS

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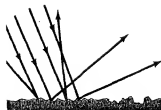


FIGURE 28.5 Even in diffuse reflection, $i = r$ for the individual rays.

in Fig. 28.4b. The velocity vector can be resolved into two components, one parallel to the surface and one perpendicular to the surface, as in the figure. Experiment shows (and theory can be shown to predict) that the velocity component perpendicular to the surface is reversed upon reflection. The other component remains unchanged. This results in the situation in Fig. 28.4c; the reflected wave is also a plane wave.

One can easily see that the four angles labeled θ in Fig. 28.4c are equal to each other. As a result, we conclude that the reflected ray will have an angle of reflection r that equals the angle of incidence i , where these angles are defined in Fig. 28.4d. Much of our study of reflection will be based upon this simple fact, called the *law of reflection*: *The angle of incidence equals the angle of reflection, and the incident and reflected rays are in the same plane.*

Reflection such as this from mirrorlike surfaces is called *specular reflection*. We have proved that the law of reflection applies in such a situation. The law is also applicable to reflection from a rough surface if we apply it to microscopic sections of the surface. To see this, refer to Fig. 28.5, which shows a highly magnified portion of a rough surface. As we see, a bundle of rays is reflected off in many directions from such a surface, so the law of reflection does not apply to the bundle as a whole. This type of reflection is called *diffuse reflection*. If we examine each individual ray, however, we see that it reflects in conformity with the law.

Although we have considered only plane waves, the angles of incidence and reflection are equal for nonplanar waves as well. Can you justify this?

28.3 Plane Mirrors

Let us now consider the formation of an image by the reflection of light waves from a plane mirror. (Even though we shall use light waves for this particular discussion, the development will be seen to apply to all wave types.) When viewing an image of an object in a mirror, one is really seeing the light emitted (or reflected) from the object. A typical case is shown in Fig. 28.6. The rays of light coming from the source S obey the usual law of reflection at the mirror,

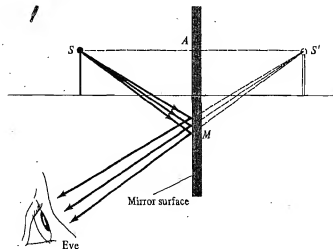


FIGURE 28.6 Using the fact $i = r$, show that the angle $\angle SMS'$ is an isosceles angle and that the image S' is as far behind the mirror as S is in front of it.

and enter the eye of the observer. Assuming the rays to have traveled in a straight line, the observer concludes they came from S' . We therefore see an image of S at point S' .

Since the angle of incidence equals the angle of reflection, the triangle $SMS'S'$ is an isosceles triangle. Therefore $SA = S'A$, and so the image of S , namely, S' , is as far behind the mirror as S is in front of it. We conclude from this that a plane mirror gives rise to an image the same size as the object. This type of image, one through which the observed rays do not actually pass, is called a virtual, or imaginary, image. In other words, the rays reaching the eye do not really come from the point they seem to come from. There is no possibility whatsoever that a sheet of paper placed at S' behind the mirror would have a lighted object appear on it. The mind merely imagines that the light comes from S' . It is always true, of course, that an object in front of a plane mirror gives rise to a virtual image. The image is always exactly as far behind the mirror as the object is in front of the mirror, as demonstrated in the figure.

Example 28.1 Find the positions of the images of S formed by the two plane mirrors shown in Fig. 28.7a. Where must one look to see each?

Reasoning There are three possible images, shown as S'_1 , S'_2 , and S'_3 . Notice that S'_1 and S'_3 are the images of S we would expect to see in the two mirrors. They are the usual virtual images of the real object S .

But image S'_1 sits in front of the (extended) surface of the mirror on the left. It acts as an object, a *virtual object*, so called because there is really nothing of substance at that position, for the mirror. Its image in the mirror is S'_2 , as shown in Fig. 28.7d.

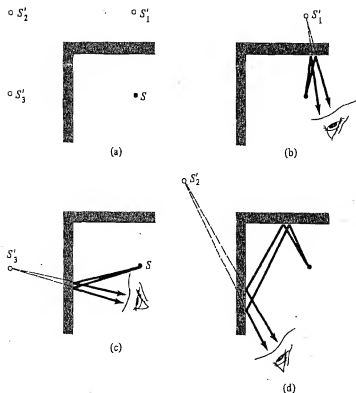


FIGURE 28.7 Must the eye be placed as shown to see the various images?

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The image is formed 12 cm from the lens, and is *real* as it will always be when s' has a positive sign. In this instance it is *inverted*, corresponding to the diagram of Fig. 3E (see also Sec. 3.8 for the analytical method of determining this). These results can be readily checked by either of the two graphical methods presented above.

3.7. Convention of Signs. The following set of sign conventions will be adhered to throughout the following chapters on geometrical optics, and it would be well to have them firmly in mind:

1. All figures are drawn with the light traveling from left to right.
2. All object distances (s) are considered as positive when they are measured to the left of the lens, and negative when they are measured to the right.
3. All image distances (s') are positive when they are measured to the right of the lens, and negative when to the left.
4. Both focal lengths are positive for a converging lens and negative for a diverging lens.
5. Transverse directions are positive when measured upward from the axis and negative when measured downward.

With regard to the signs of radii of curvature, see Sec. 3.10.

3.8. Magnification. In any optical instrument the ratio between the transverse dimension of the final image and the corresponding dimension of the original object defines the *lateral magnification*. A simple formula for the magnification by a single lens may be derived from the geometry of Fig. 3F. By construction it is seen that the right triangles QMA and $Q'M'A$ are similar. Corresponding sides are therefore proportional to each other, so that

$$\frac{M'Q'}{MQ} = \frac{AM}{AM'}$$

where AM' is the image distance s' and AM is the object distance s . Taking upward directions as positive, $y = MQ$ and $y' = -Q'M'$, so we have by direct substitution $y'/y = -s'/s$. The lateral magnification is therefore

$$m = \frac{y'}{y} = -\frac{s'}{s} \quad (3c)$$

When s and s' are both positive, as in Fig. 3F, the negative sign of the magnification signifies an inverted image.

3.9. Virtual Images. The images formed by the converging lenses in Figs. 3E and 3F are real in that they can be made visible on a screen. They are characterized by the fact that rays of light are actually brought

to a focus in the plane of the image. A virtual image (Sec. 2.3) cannot be formed on a screen. The rays from a given point on the object do not actually come together at the corresponding point in the image; instead they must be projected backward to find this point. Virtual images are produced with converging lenses when the object is placed closer to the lens than the focal point, and by diverging lenses when the object is in any position. Examples of these cases are shown in Figs. 3H and 3I.

Figure 3H shows the parallel-ray construction for the case where a positive lens is being used as a magnifier, or reading glass. Rays emanating from Q are refracted by the lens but are not sufficiently deviated to come to a real focus. To the observer's eye at E these rays appear to be com-

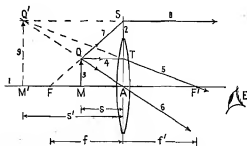


FIG. 3H. Parallel-ray method of construction for the location of the virtual image formed by a positive lens when the object lies inside of the focal point.

ing from a point Q' in back of the lens. This represents a virtual image, because the rays do not actually pass through Q' ; they only appear to come from there. Here the image is right side up and magnified. In the construction of this figure, ray QT parallel to the axis is refracted through F' , while ray QA through the center of the lens is undeviated. These two rays when extended backward intersect at Q' . The third ray QS , traveling outward as though it came from F , actually misses the lens, but if the latter were larger the ray would be refracted parallel to the axis, as shown. When projected backward it also intersects the other projections at Q' .

As an example consider an object placed 6 cm in front of a converging lens of focal length 10 cm, and let it be required to find the image. Direct substitution in Eq. 3b gives

$$\frac{1}{6} + \frac{1}{s'} = \frac{1}{10}, \quad \frac{1}{s'} = \frac{1}{10} - \frac{1}{6} = \frac{3}{30} - \frac{5}{30} = -\frac{2}{30}$$